Non-thermal Mg I emission at 12 μm from Procyon

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ABSTRACT

We report on stellar Mg I emission at $12\,\mu$m from α CMi (Procyon), a star slightly hotter than the Sun. Solar Mg I emission is well-known and its formation was successfully explained in detail by Carlsson et al. (1992). Here, for the first time, we compare synthetic spectra of the emission lines at $12\,\mu$m with observations of a star other than the Sun. The use of these lines as stellar diagnostics has been anticipated for 10 years or more (see, e.g., Carlsson et al. 1992). We find that the model reproduces the observed emission in Procyon quite well. We expect that high-resolution spectrographs on $8-10$ m telescopes will finally be able to exploit these new diagnostics.

Subject headings: stars: individual (α CMi) – stars: atmospheres– Infrared: stars

1. Introduction

The origin and formation process of the once enigmatic *solar* Mg I emission at 811.578 cm^{-1} (12.3217 μm) and 818.058 cm^{-1} (12.2241 μm) was first explained successfully and in

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detail by Carlsson et al. (1992, hereafter CRS). By employing an extensive model atom of Mg I in a full Non Local Thermodynamic Equilibrium (NLTE) calculation, they concluded the emission lines were photospheric in origin. CRS accounted excellently for the emission strengths of the Mg I lines, their complicated intensity profiles as a function of viewing angle on the solar disk, and the relative strengths of several Mg I lines, both in emission and absorption. Furthermore, CRS could explain the similar but weaker Si I and Al I emission features observed in the solar spectrum. Baumüller & Gehren (1996) successfully modeled these Al I emission-features in the Sun, showing that a similar NLTE effect as for Mg I is responsible. Zhao et al. (1998) were also able to reproduce the solar emission lines with a similar NLTE analysis of magnesium in the solar photosphere. Moreover, by including artificially reduced, inelastic, neutral-hydrogen collisions, they were also able to simultaneously model line cores of visual and near-infrared (NIR) Mg I absorption-lines in the range of $4\,500 - 12\,000$ Å.

The Mg I emission lines at 12 μm in the Sun clearly show Zeeman splitting and so trace the local magnetic field (Brault & Noyes 1983; Bruls et al. 1995). Because Zeeman splitting depends on the square of the wavelength while Doppler broadening goes as the first power, mid-infrared lines better reveal Zeeman splitting than optical or NIR lines with the same Landé g-factor. Thus, these lines potentially offer an excellent method for measuring stellar disk-averaged magnetic fields, and will be complementary to studies using NIR lines in that they will probe other atmospheric layers and are more Zeeman sensitive.

In this paper we report on our detection and modeling of the mid-infrared Mg I emission features in Procyon, an F5IV-V star. In the Sun, the observed emission lines are formed as a result of a NLTE flow cycle. As lines originating from high-excitation levels become optically thin in the photosphere, lower lying levels are overpopulated and subsequently photoionized. The Mg II reservoir refills the high-excitation levels via Rydberg states of Mg I, leading to the emission. From NLTE calculations, the relevant departures from Boltzmann level-populations for the levels involved – $3s7i^{1,3}\mathrm{I}^e$ and $3s6h^{1,3}\mathrm{H}^o$ for the 811.6 cm^{-1} line and $3s7h^{1,3}\mathrm{H}^o$ and $3s6g^{1,3}\mathrm{G}^e$ for the 818.1 cm^{-1} line – are quite similar for both the upper and lower states. The departure coefficients of the upper levels are of the order of 10% larger than those of the lower states. However, this small difference between the level departures is the direct cause of the observed emission.

2. Observations

We observed Procyon with the Texas Echelon-Cross-Echelle Spectrograph (TEXES, Lacy et al. 2002), a visitor instrument at the 3m NASA Infrared Telescope Facility (IRTF). The raw data were collected during November 2000, November 2001, December 2002, De-

cember 2003, and January 2004. Separate grating settings were required for each Mg I line.

We used the cross-dispersed, high spectral resolution mode for all observations. Observations of unresolved line sources indicate that the core of the line profile at this wavelength is reasonably reproduced with a Gaussian with FWHM = $3.5 \, \mathrm{km \, s^{-1}}$ ($R \sim 86\,000$) and wings that are slightly broader than Gaussian.

Data acquisition and reduction followed the standard procedure described in Lacy et al. (2002). To remove sky and telescope background, Procyon was nodded along the slit. Wavelength calibration was done using telluric atmospheric lines; previous experience shows this procedure typically gives accuracy better than $1 \, \mathrm{km \, s^{-1}}$. After reducing a given data set, we normalized the continuum using a 6th order Legendre polynomial and then combined appropriate data files. Procyon has almost no photospheric features at this wavelength so determining the continuum is easy and reliable. Furthermore, the telluric atmosphere at the Mg I wavelengths is very clean. Slight variations in wavelength setting from night-to-night result in increased noise where less data could be coadded.

3. Modeling

We have analyzed the Procyon Mg I lines as CRS successfully did for the Mg I lines in the Sun. We use a one-dimensional, hydrostatic, flux-conserved, non-magnetic, LTE model for the physical structure of the atmosphere. The model-atmosphere, including the specific, mean-intensity field at all depths, is calculated with the MARCS code, which was first developed by Gustafsson et al. (1975) and has been successively updated ever since (Gustafsson et al. 2004, in preparation).

For the line formation of Mg I and the spectral synthesis, a full NLTE calculation is performed using the program MULTI (Carlsson 1986). Our Mg I model atom was kindly provided by Mats Carlsson. We require our model to reproduce the excellent fits of the intensity profiles measured at different locations on the solar disk as presented in CRS. We solve the equations of statistical equilibrium for the magnesium atom level populations at each of 66 levels, including 315 line transitions and 65 bound-free transitions (ionization and recombination). One Mg II level is included. We calculate photoionization rates by incorporating the calculated specific, mean-intensity field for all depths from the model atmosphere. This treatment allows the full line-blanketing to be considered through ultraviolet wavelengths, which mainly affect the photoionization from the lowest states. For a further discussion, references for the atomic data, and the uncertainties in the modeled emission, see CRS.

The fundamental stellar parameters of Procyon, needed in the calculation of the model

atmosphere, are relatively well known. All parameters, except the metallicity, can be derived from direct measurements. Recent works determining Procyon's parameters include, Fuhrmann (1998), Allende Prieto et al. (2002), and Korn et al. (2003). The parameters we have used are: an effective temperature of $T_{\mathrm{eff}} = (6\,512 \pm 50)$ K, a surface gravity of $\log g = 3.96 \pm 0.02$ (cgs units), a mass of $M = (1.42 \pm 0.06)\,M_{\odot}$, and a radius of $R = (2.07 \pm 0.02)\,R_{\odot}$ (Allende Prieto et al. 2002). The metallicity (iron abundance) of the star is slightly lower than solar. Fuhrmann (1998) measures a slightly super-solar α-element abundance. Nevertheless, we will assume a solar abundance mixture as given by Grevesse & Sauval (1998). We model the atmosphere with a depth-independent micro-turbulence parameter of $\xi_{\mathrm{micro}} = 2.0$ km s^{-1}, in agreement with current literature.

4. Results and discussion

Our model and observations are shown in Figure 1 and 2. In order to match the line widths, we introduce the customary artifice of macroturbulent broadening, including the instrumental profile. We assume the broadening velocities have a Gaussian distribution with a FWHM of 9.5 km s^{-1}, which is slightly larger than that given in Allende Prieto et al. (2002). We find the model reproduces the disk-averaged observations within the modeling uncertainties. In a forthcoming paper we will investigate our calculation by discussing the atomic model of Mg I and the assumptions made in our NLTE calculation, such as the collisional rates, atmospheric radiation field used and the validity of the assumption of atmospheric homogeneity.

In Figure 3, the departure coefficients (defined as in CRS) of the relevant levels are plotted as a function of depth in the atmosphere, shown as the optical depth calculated in the continuum at 500 nm. The departure coefficients are very similar to the solar case, indicating that the same formation process of the Mg I emission lines is at play for Procyon. Following CRS, we have included 'quasi-elastic l-changing'[1] collisions with neutral particles, which keep all close-lying Rydberg states with common principal quantum-numbers n in relative thermalization. This means that the departure coefficients of the upper and lower states, respectively, of the two Mg I emission lines will follow each other exactly since they have the same n quantum numbers. Thus, in Figure 3 the upper and lower levels of the two Mg I emission lines fall on top of each other. The lower levels depart more from LTE. Whereas for the Sun the population of Mg II is slightly larger than that of LTE, for Procyon the Mg II population is very close to LTE.

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[1]l being the azimuthal quantum number

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The Mg I emission in Procyon is only marginally larger than that of the Sun. This fact can qualitatively be understood as follows. The higher temperatures in Procyon compared to the Sun, will lead to a larger ionization of magnesium, with a factor of ten less Mg I expected all through the line-forming regions. However, in the line-forming regions of Procyon, the 500 K warmer temperatures compared to the Sun, also lead to roughly a factor of ten more atoms excited to the levels involved in the formation of the emission line. Since the departure coefficients for both Procyon and the Sun are quite similar, the resulting emission will be of the same order of magnitude, as observed.

To conclude, we have shown that, with a NLTE calculation using the CRS model atom of magnesium, it is possible to reproduce Mg I emission lines at 12 μm successfully, not only for the Sun but also for Procyon. This is the first star, other than the Sun, that this has been done for. Future investigations of different types of stars, showing Mg I emission lines, will also be important. The Mg I emission lines should be useful tools for measuring stellar magnetic-fields through their Zeeman splitting. After a decade of anticipation, high-resolution, mid-IR spectrographs, such as TEXES, at 8-10 m telescopes will now allow the use of the Mg I 12 μm lines for stellar magnetic-field diagnostics.

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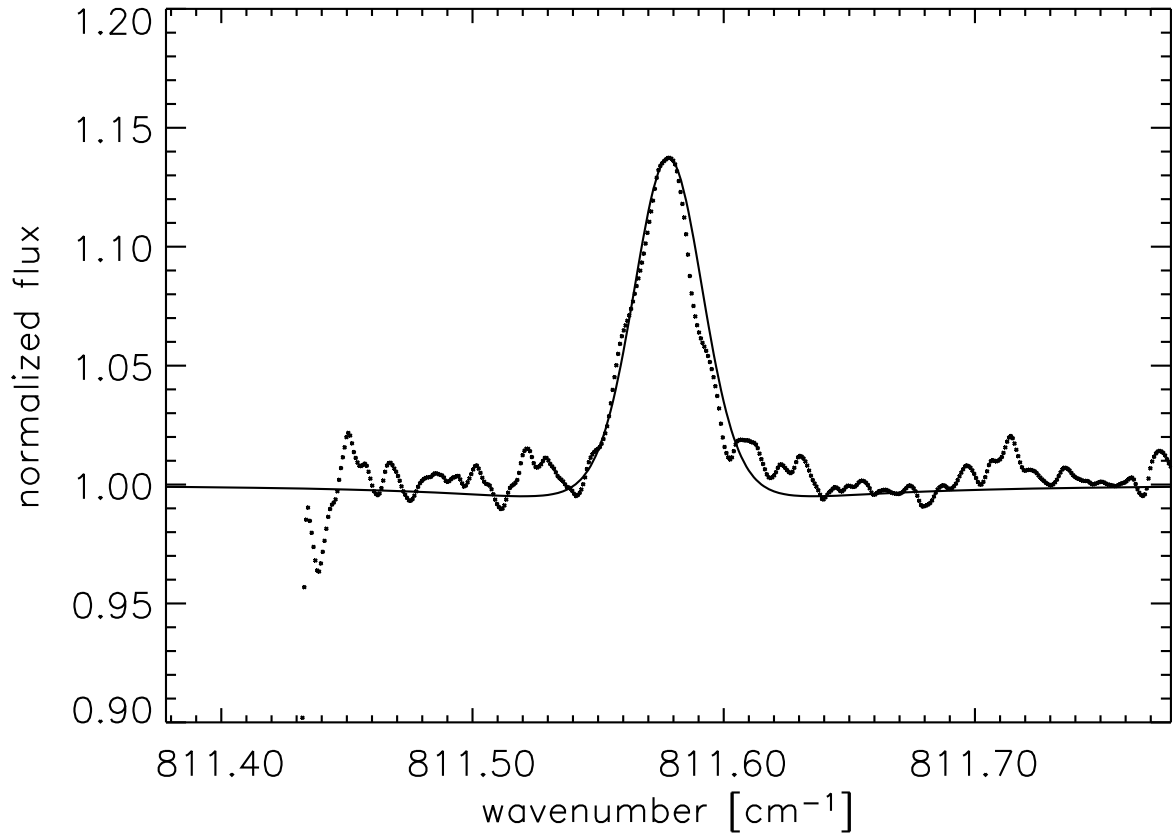
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Fig. 1.— Dotted line shows the Mg I emission-line at 811.578 cm^{-1} (12.3217 μm) observed from Procyon and the full line shows the model.
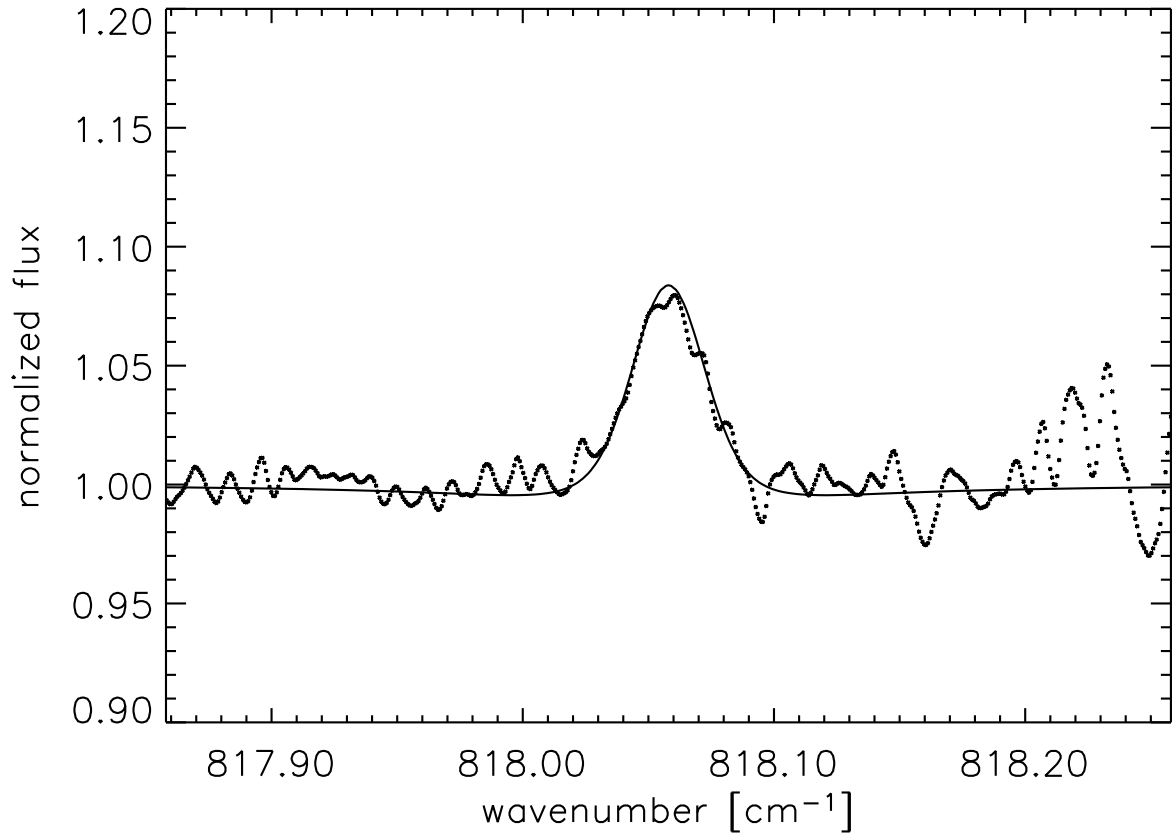
Fig. 2.— Dotted line depicts the 818.058 cm^{-1} (12.2241 μm) Mg I line observed from Procyon. As in Figure 1, the model prediction is shown by a full line.
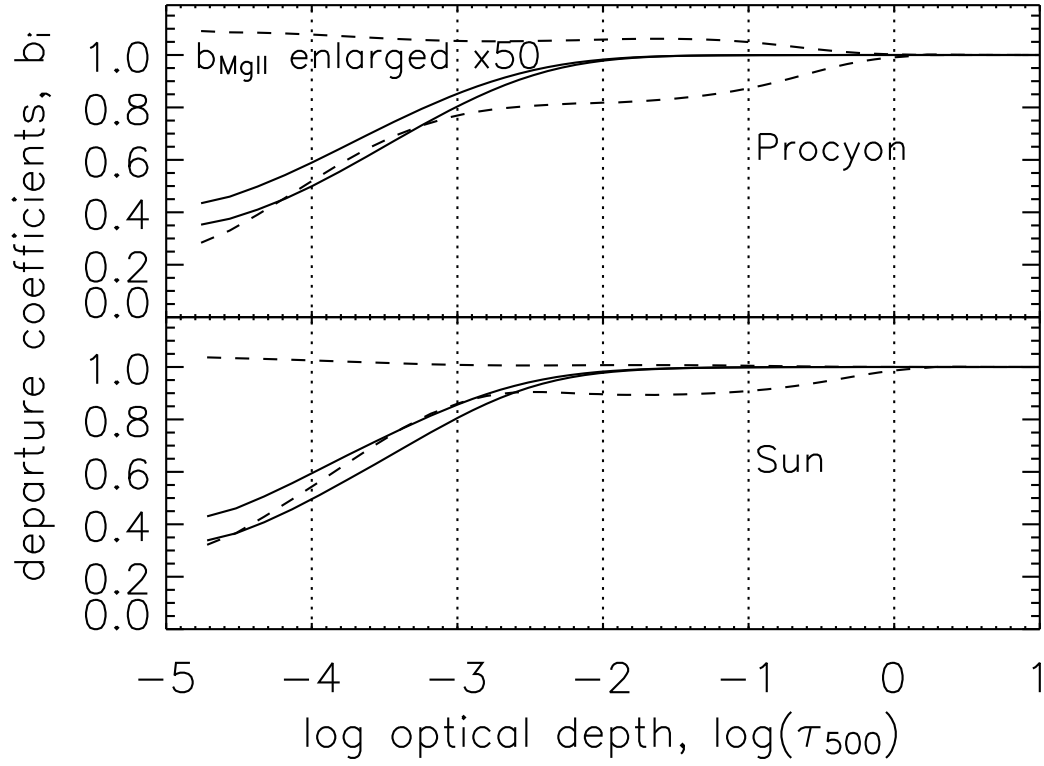
Fig. 3.— Departure coefficients for the levels involved in the two emission lines are shown with full lines. The upper dashed line shows the departure coefficient of Mg II and the lower dashed line shows the ground level of Mg I.